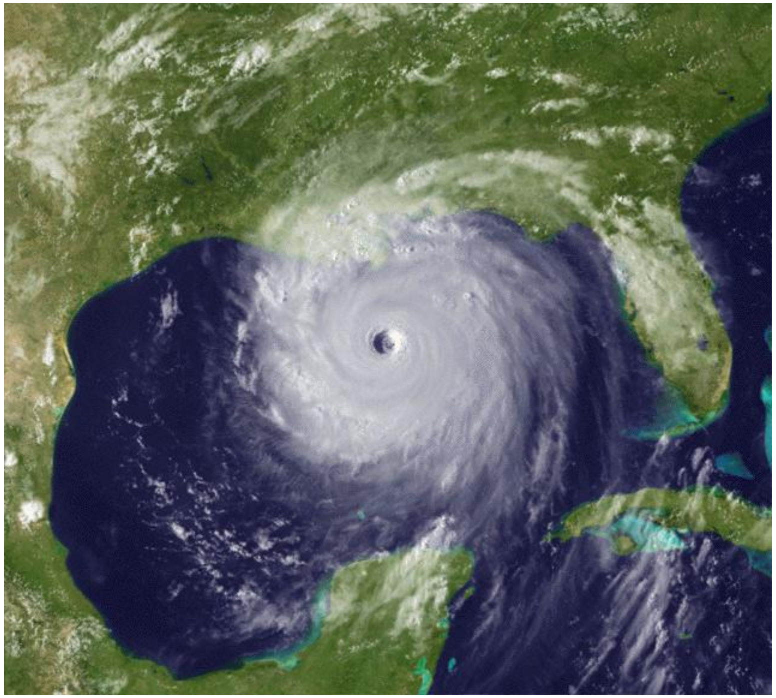
Tropical Cyclones and Climate Change



Hurricane Katrina (2005), damage estimate: ~$US125 Billion

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Tropical cyclones and climate change

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World Meteorological Organization
Weather Research Programme

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Overview of Assessments

Climate Change Detection and Attribution:

- It remains uncertain whether past changes in tropical cyclone activity exceed natural variability levels.

Projections for late 21st century:

- Likely fewer tropical storms globally (~no change to -34%), with even greater uncertainty in individual basins (e.g., the Atlantic).

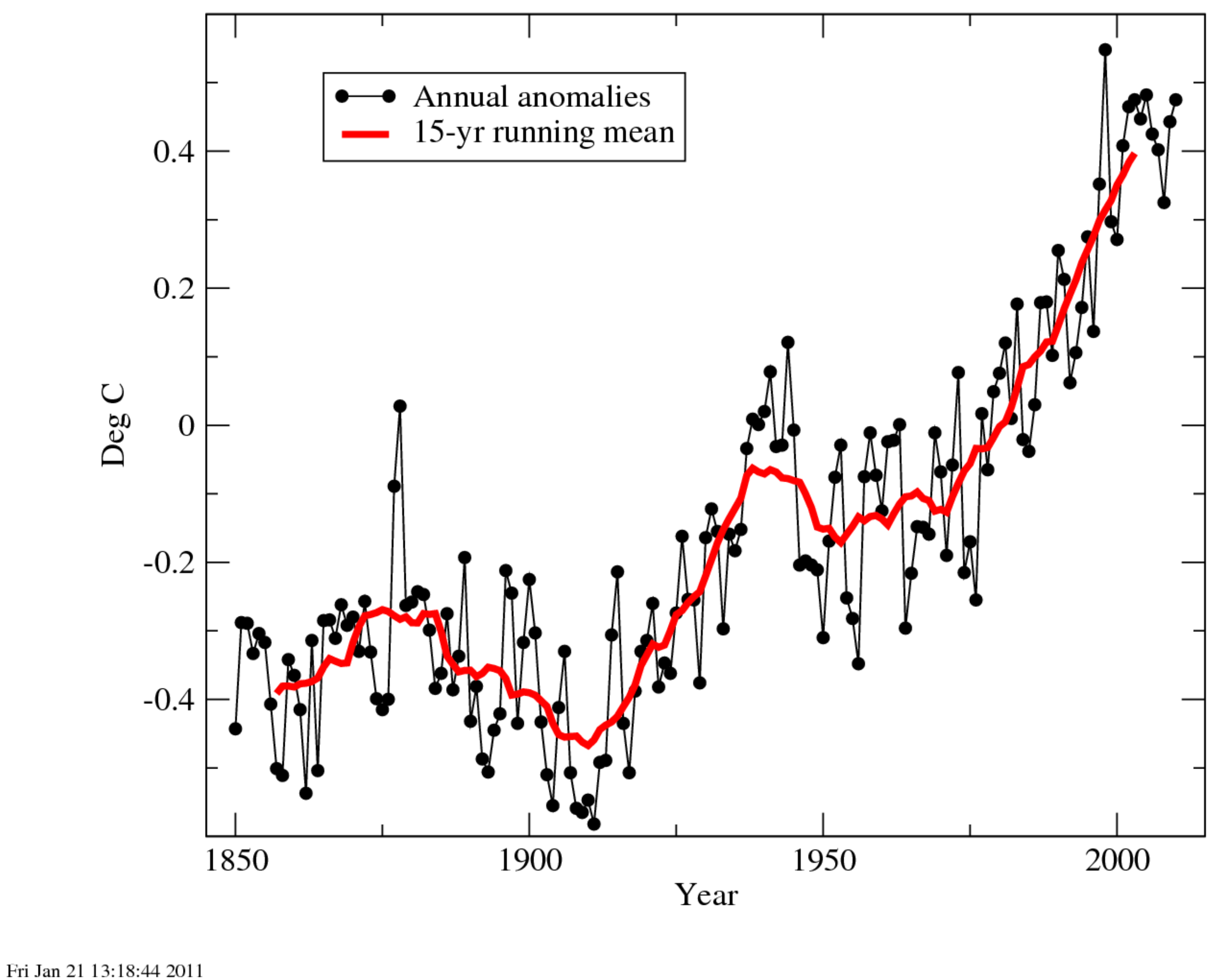
- Likely increase in average hurricane wind speeds globally (+2 to11%), though not necessarily in all basins

- More likely than not (>50% chance) that the frequency very intense hurricanes will increase by a substantial fraction in some basins

- Likely higher rainfall rates in hurricanes (roughly +20% within 100 km of storm)

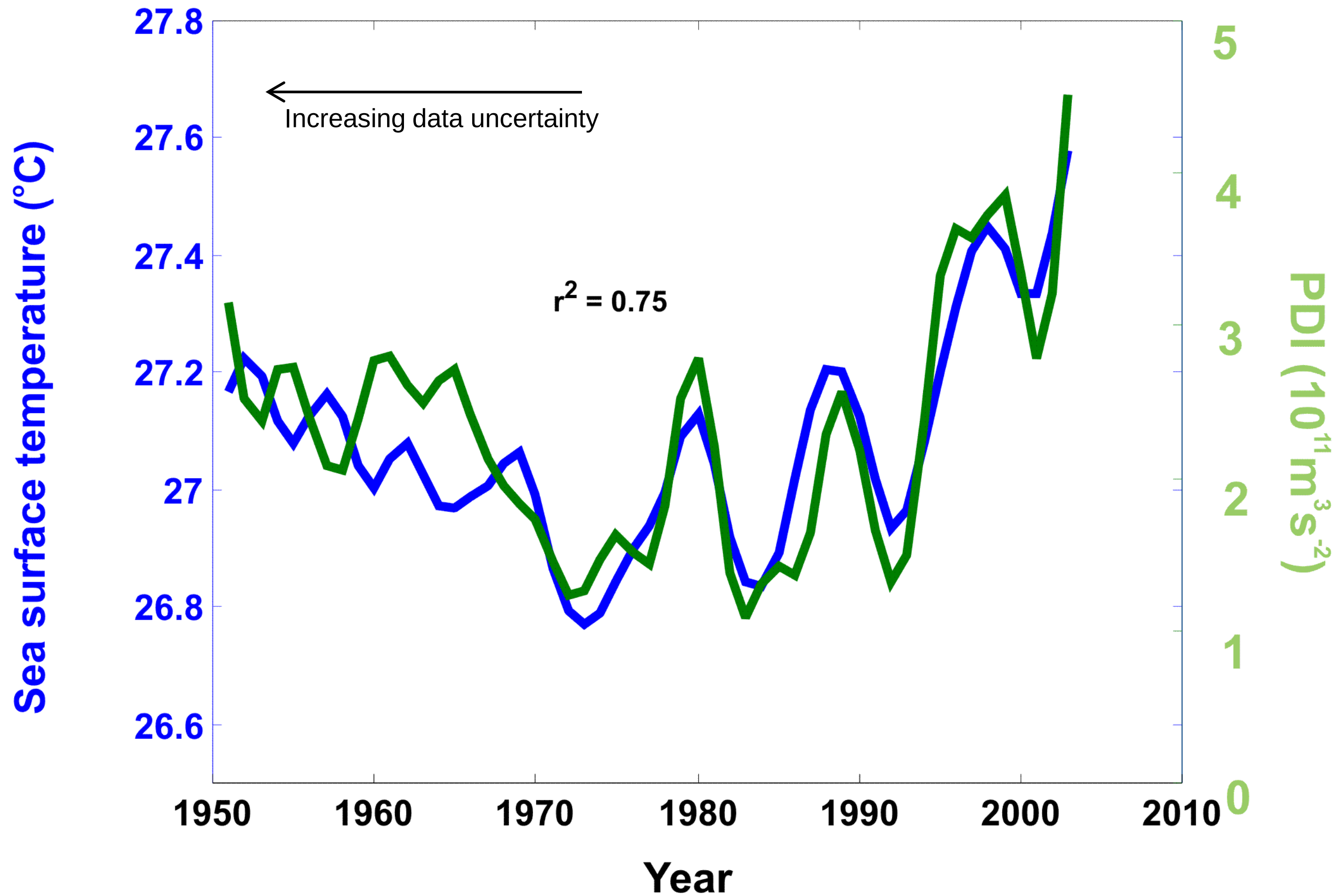
- Sea level rise is expected to exacerbate storm surge impacts even assuming storms themselves do not change.

HadCRUT3 global mean temperature anomalies (1850-2010)



Source: Climatic Research Unit. http://www.cru.uea.ac.uk/cru/data/temperature/

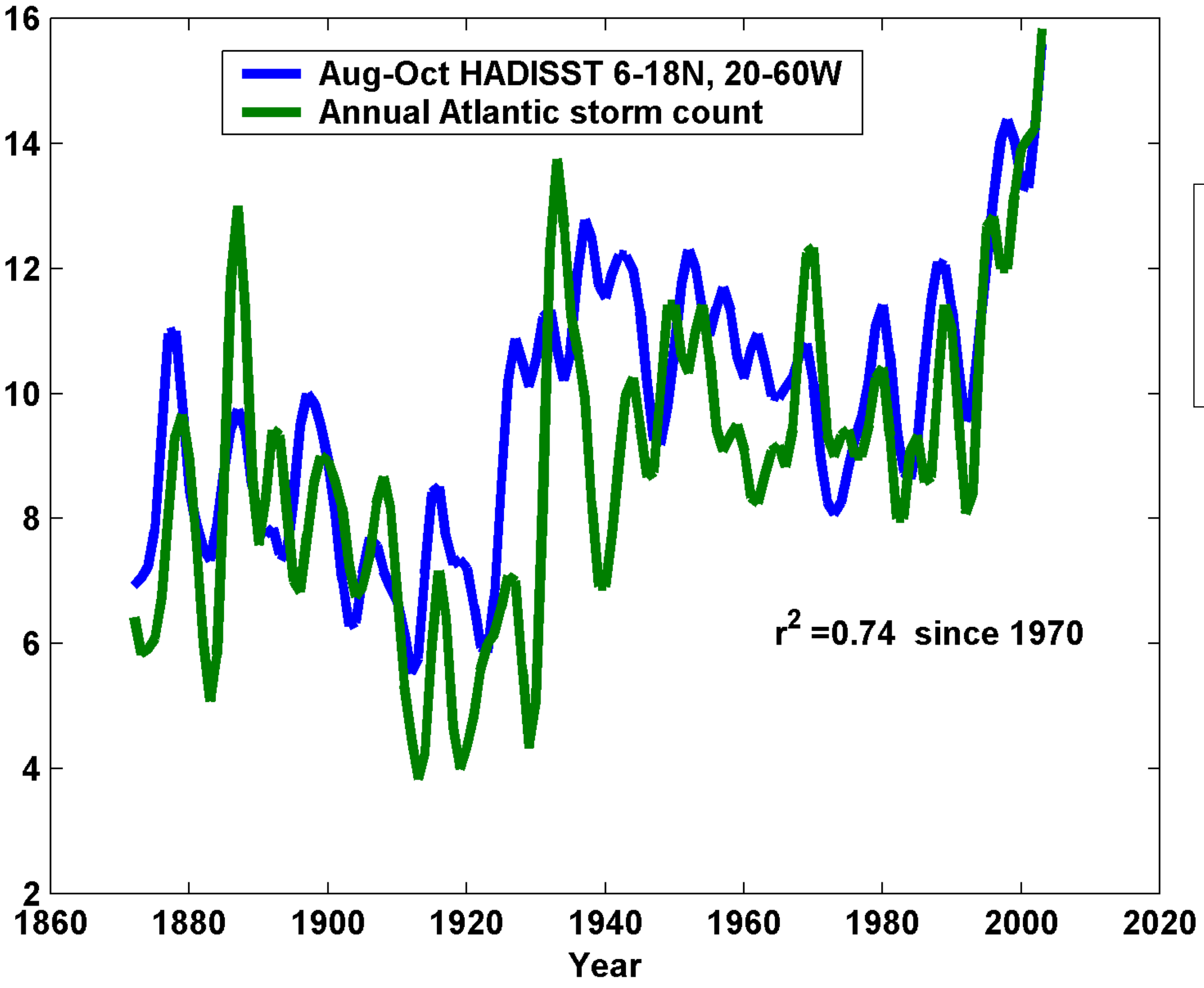
There is some recent evidence that overall Atlantic hurricane activity may have increased since in the 1950s and 60s in association with increasing sea surface temperatures…



PDI is proportional to the time integral of the cube of the surface wind speeds accumulated across all storms over their entire life cycles.

Source: Kerry Emanuel, J. Climate (2007).

The frequency of tropical storms (low-pass filtered) in the Atlantic basin since 1870 has some correlation with tropical Atlantic SSTs

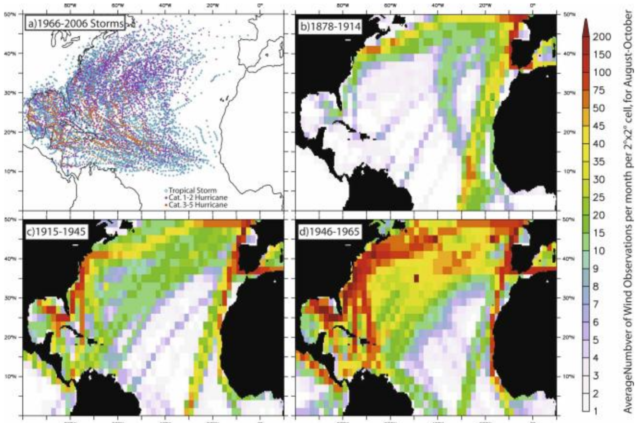


But is the storm record reliable enough for this?

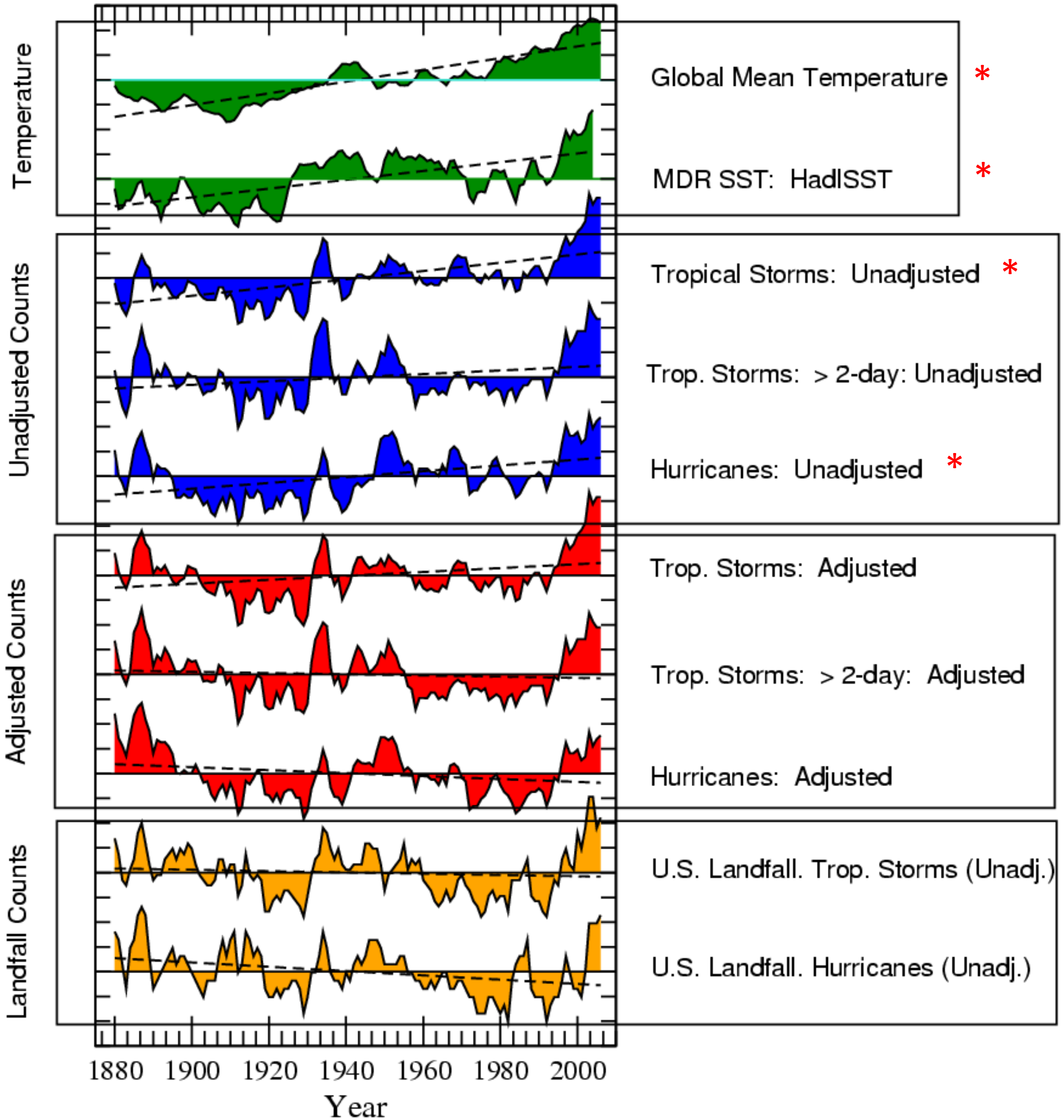
Source: Emanuel (2006); Mann and Emanuel (2006) EOS. See also Holland and Webster (2007) *Phil. Trans. R. Soc. A*

* => Significant at p=0.05

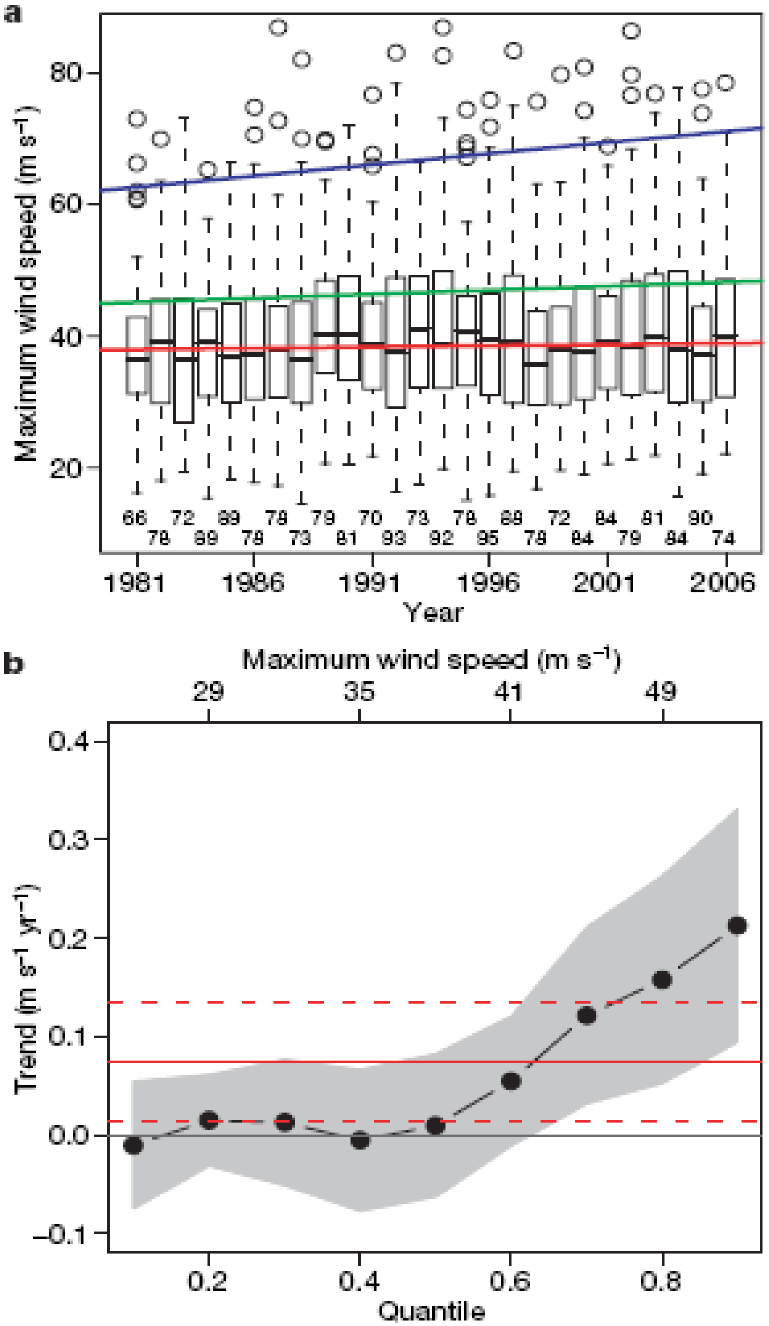
Adjustments to storm counts based on ship/storm track locations and density



Normalized Tropical Atlantic Indices



Sources:
- Vecchi and Knutson (2008)
- Landsea et al. (2009)
- Vecchi and Knutson (in press)



Global Tropical Cyclone Intensity Trends

There is some statistical evidence that the strongest hurricanes are getting stronger. This signal is most pronounced in the Atlantic. However, the satellite-based data for the global analysis are only available for 1981-2006.

Quantile regression computes linear trends for particular parts of the distribution. The largest increases of intensity are found in the upper quantiles (upper extremes) of the distribution.

Source: Elsner et al., *Nature,* 2008

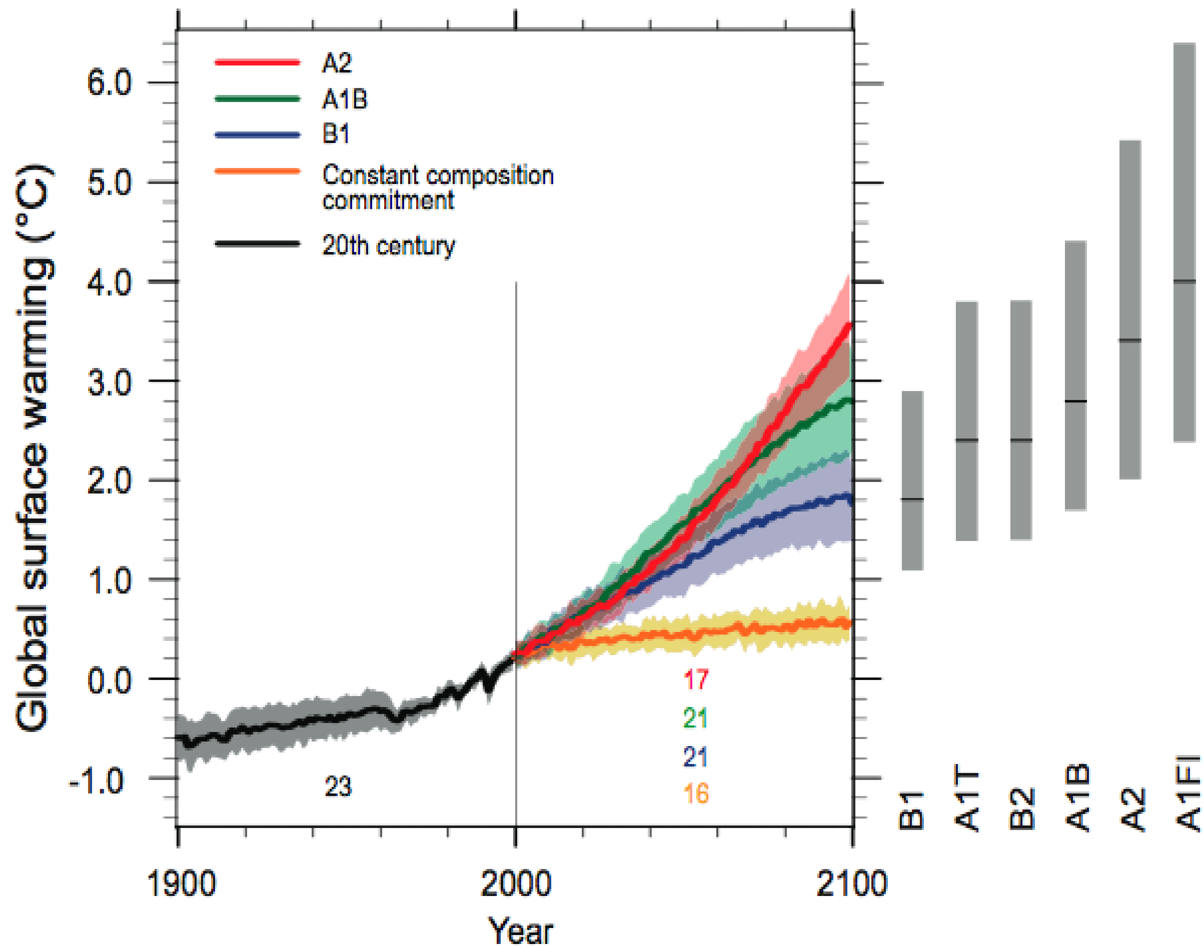
IPCC Projections of Future Changes in Climate

Global Mean Temperature Change

IPCC best estimates (with *likely* ranges):

Low scenario (B1):
1.8 C (1.1 - 2.9 C)

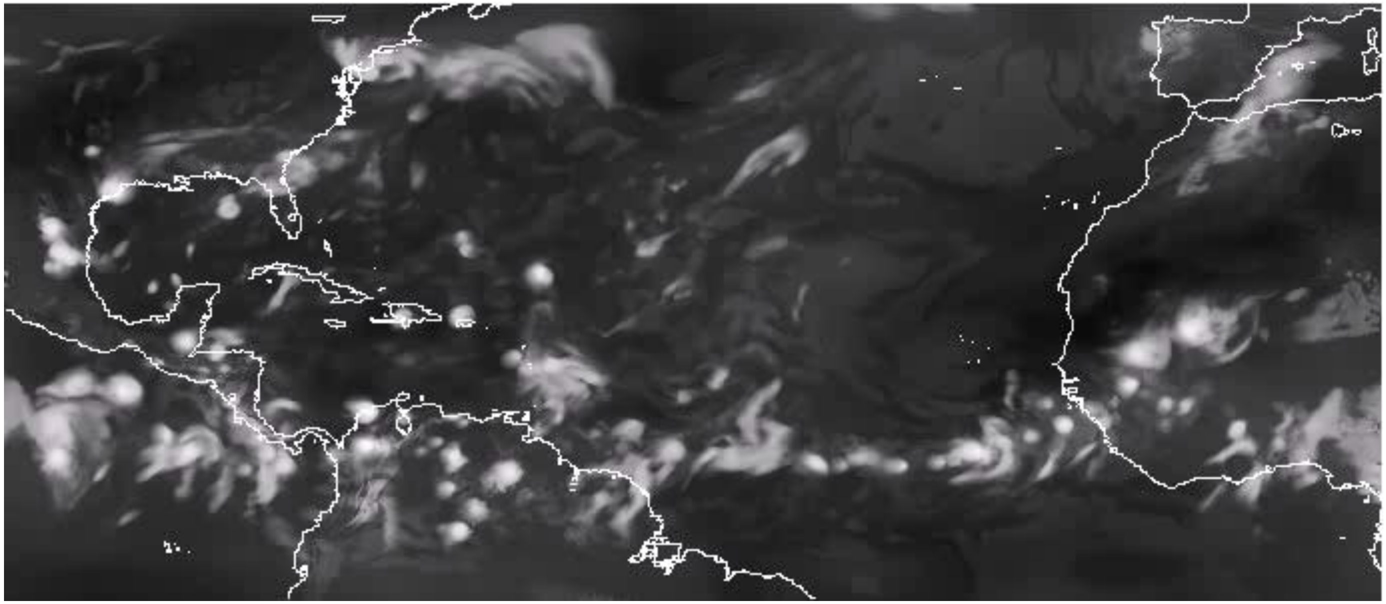
High scenario (A1FI):
4.0 C (2.4 - 6.4 C)

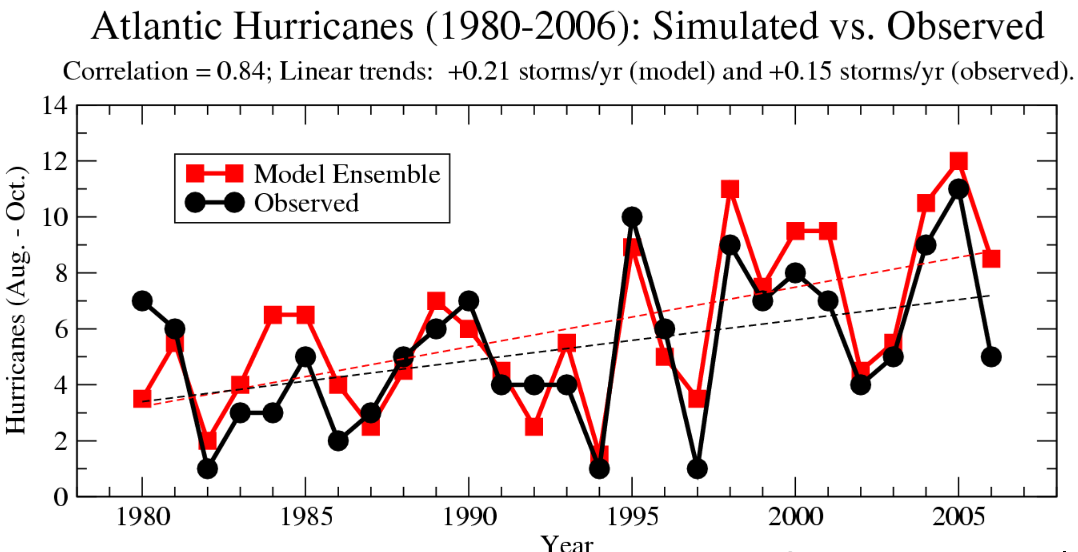


Source: IPCC 4th Assessment Report. Used with permission.

Zetac Regional Model reproduces the interannual variability and trend of Atlantic hurricane counts (1980-2006)

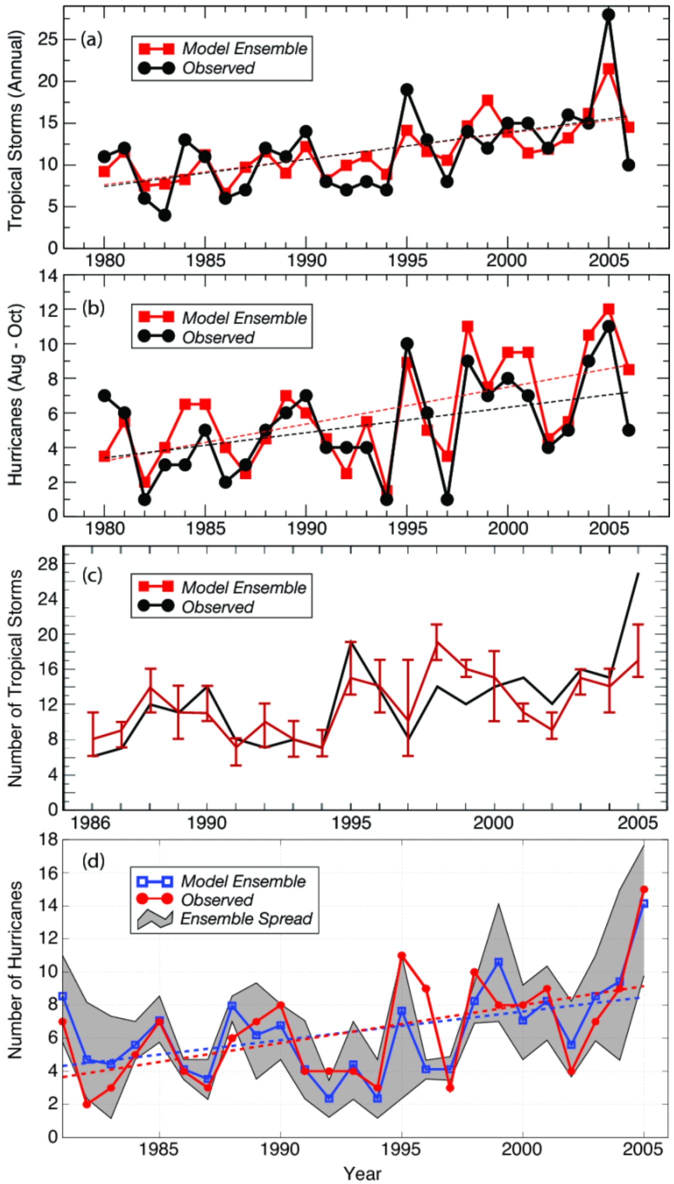
18-km grid model nudged toward large-scale (wave 0-2) NCEP Reanalyses





Source: Knutson et al., *2007*, Bull. Amer. Meteor. Soc.

Simulating past variability in Atlantic tropical cyclone activity



Progress has been made in developing dynamical and statistical/dynamical models for seasonal tropical cyclone frequency.

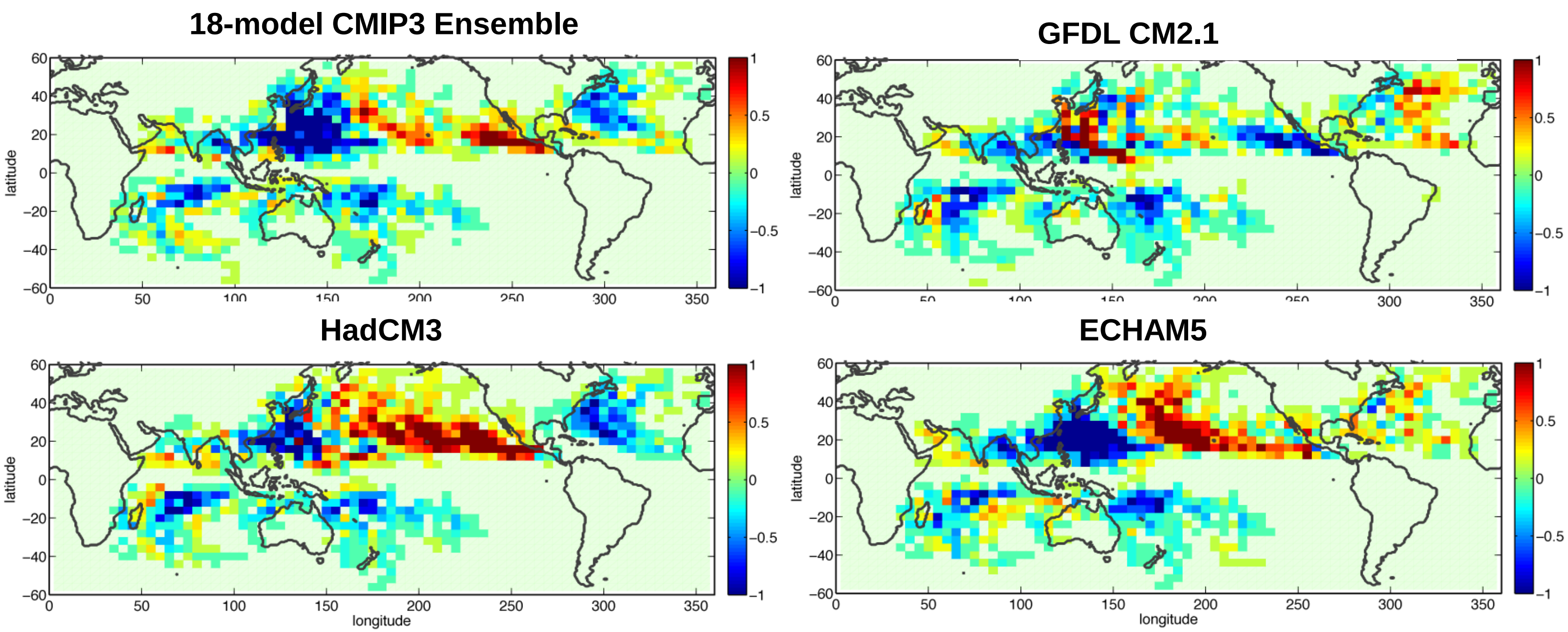
Left: examples for the Atlantic basin, using high resolution atmospheric models; regional dynamical downscaling models; and statistical/dynamical techniques.
(a) and (b) use NCEP Reanalysis.
(c) and (d) use only SSTs.

<u>Current question</u>: Is the cooling of tropopause transition layer (TTL) temperatures crucial for simulating the Atlantic trend in TCs over this period?

Source: Knutson et al., Nature Geoscience (2010).

Projected Changes in Regional Hurricane Activity

GFDL 50-km HIRAM, using four projections of late 21st Century SSTs.



Red/yellow = increase
Blue/green = decrease

Unit: Number per year

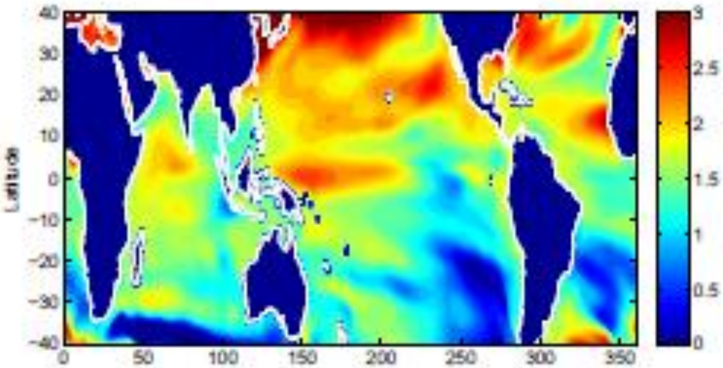
- Regional increases/decreases much larger than global-mean.
- Pattern depends on details of SST change.

Source: Courtesy Ming Zhao, GFDL. Adapted from Zhao, et al. (J. Climate, 2009)

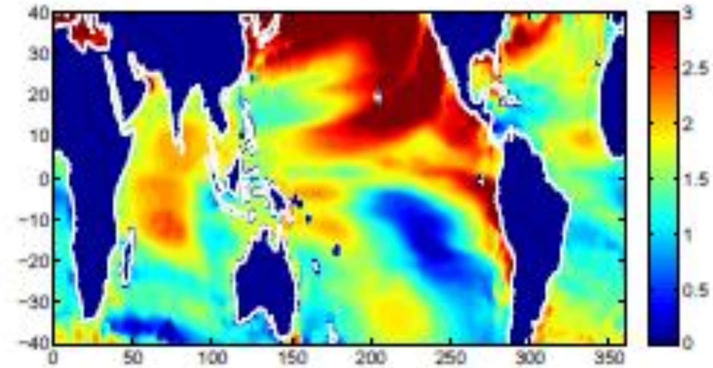
Global Model Tropical Cyclone Climate Change

Experiments: Use A1B Scenario late 21st century projected SST changes from several CMIP3 models

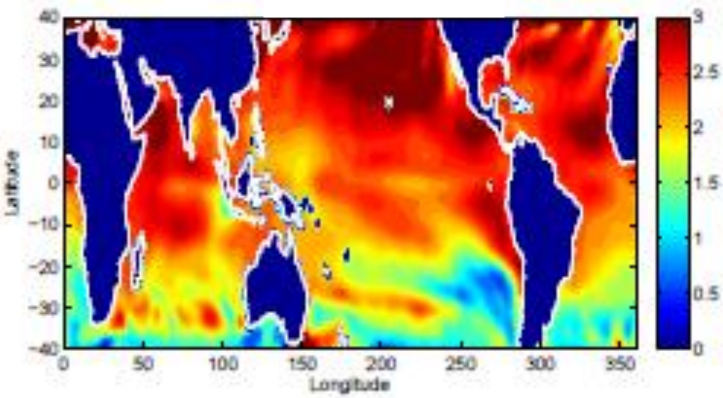
GFDL CM2.1



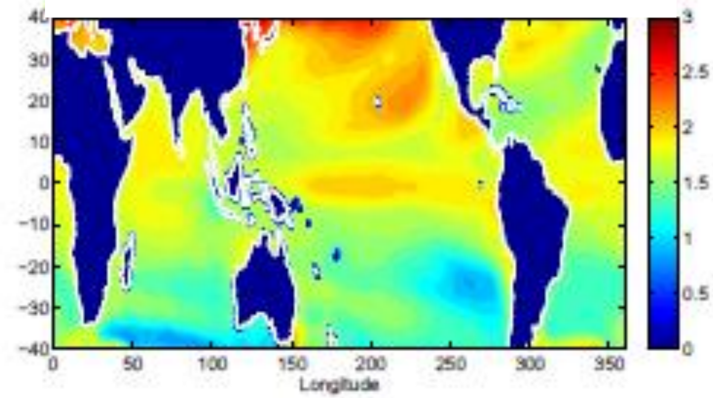
HadCM3



ECHAM5



CMIP3 18-model Ensemble



Source: Zhao, Held, Lin, and Vecchi (J. Climate, 2009)

Unit: Deg C

TABLE S1. TC Frequency Projections												
Reference	Model/type	Resolution/	Experiment	Basin								
				Global	NH	SH	N Atl.	NW Pac.	NE Pac	N Ind	S Ind	SW Pac
Tropical Storm Frequency Changes (%)												
Sugi et al. 2002 (ref 36)	JMA Timeslice	T106 L21 (~120km)	10y 1xCO2, 2xCO2	-34	-28	-39	+61	-66	-67	+9	-57	-31
McDonald et al. 2005 (ref 53)	HadAM3 Timeslice	N144 L30 (~100km)	15y IS95a 1979-1994 2082-2097	-6	-3	-10	-30	-30	+80	+42	+1 0	-18
Hasegawa and Emori 2005 (ref 54)	CCSR/NIES/FRC GC timeslice	T106 L56 (~120km)	5x20y at 1xCO2 7x20y at 2xCO2					-4				
Yoshimura et al. 2006 (ref 55)	JMA Timeslice	T106 L21 (~120km)	10y 1xCO2, 2xCO2	-15								
Oouchi et al. 2006 (ref 10)	MRI/JMA Timeslice	TL959 L60 (~20km)	10y A1B 1982-1993 2080-2099	-30	-28	-32	+34	-38	-34	-52	-28	-43
Chauvin et al. 2006 (ref 11)	ARPEGE Climat Timeslice	~50 km	Downscale CNRM B2 Downscale Hadley A2				+18 -25					
Stowasser et al. 2007 (ref 56)	IPRC Regional		Downscale NCAR CCSM2, 6xCO2					+19				
Bengtsson et al. 2007 (ref 23)	ECHAM5 timeslice	T213 (~60 km)	2071-2100, A1B		-9		-8	-20	+4	-26		
Bengtsson et al. 2007 (ref 23)	ECHAM5 timeslice	T319 (~40 km)	2071-2100, A1B		-12		-13	-28	+7	-51		
Emanuel et al. 2008 (ref 21)	Statistical-deterministic	---	Downscale 7 CMIP3 mods.: A1B, 2180-2200 Average over 7 models	-7	-4	-14	+2	+6	-5	-8	n/a	n/a
Knutson et al. 2008 (ref 22)	GFDL Zetac regional	18 km	Downscale CMIP3 ens. A1B, 2080-2100				-27					
Leslie et al. 2007 (ref 57)	OU-CGCM with high-res. window	Up to 50 km	2000 to 2050 control and IS92a (6 members)									~0
Gualdi et al. 2008 (ref 34)	SINTEX-G coupled model	T106 (~120 km)	30 yr 1xCO2, 2xCO2, 4xCO2	-16 (2x) -44 (4x)			-14	-20	-3	-13	-14	-22
Semmler et al. 2008 (ref 58)	Rossby Centre regional model	28 km	16 yr control and A2, 2085-2100				-13					
Zhao et al. 2009 (ref 12)	GFDL HIRAM timeslice	50 km	Downscale A1B: CMIP3 n=18 ens. GFDL CM2.1 HadCM3 ECHAM5	-20 -20 -11 -20	-14 -14 +5 -17	-32 -33 -42 -27	-39 -5 -62 -1	-29 -5 -12 -52	+15 -23 +61 +35	-2 -43 -2 -25	-30 -33 -41 -13	-32 -31 -42 -48
Sugi et al. 2009 (ref 59)	JMA/MRI global AGCM timeslice	20 km 20 km 20 km 20 km 60 km 60 km 60 km 60 km	Downscale A1B: MRI CGCM2.3 MRI CGCM2.3 MIROC-H CMIP3 n=18 ens. MRI CGCM2.3 MIROC-H CMIP3 n=18 ens. CSIRO	-29 -25 -27 -20 -20 -6 -21 -22	-31 -25 -15 -21 -21 0 -19 -29	-27 -25 -42 -19 -17 -16 -25 -11	+22 +23 -18 +5 +58 +6 +4 -37	-36 -29 +28 -26 -36 +64 -14 +13	-39 -30 -50 -25 -31 -42 -33 -49	-39 -29 +32 -15 -12 +79 +33 -7	-28 -25 -24 -5 -22 +1 0 -18 -22	-22 -27 -90 -42 -8 -69 -36 +10

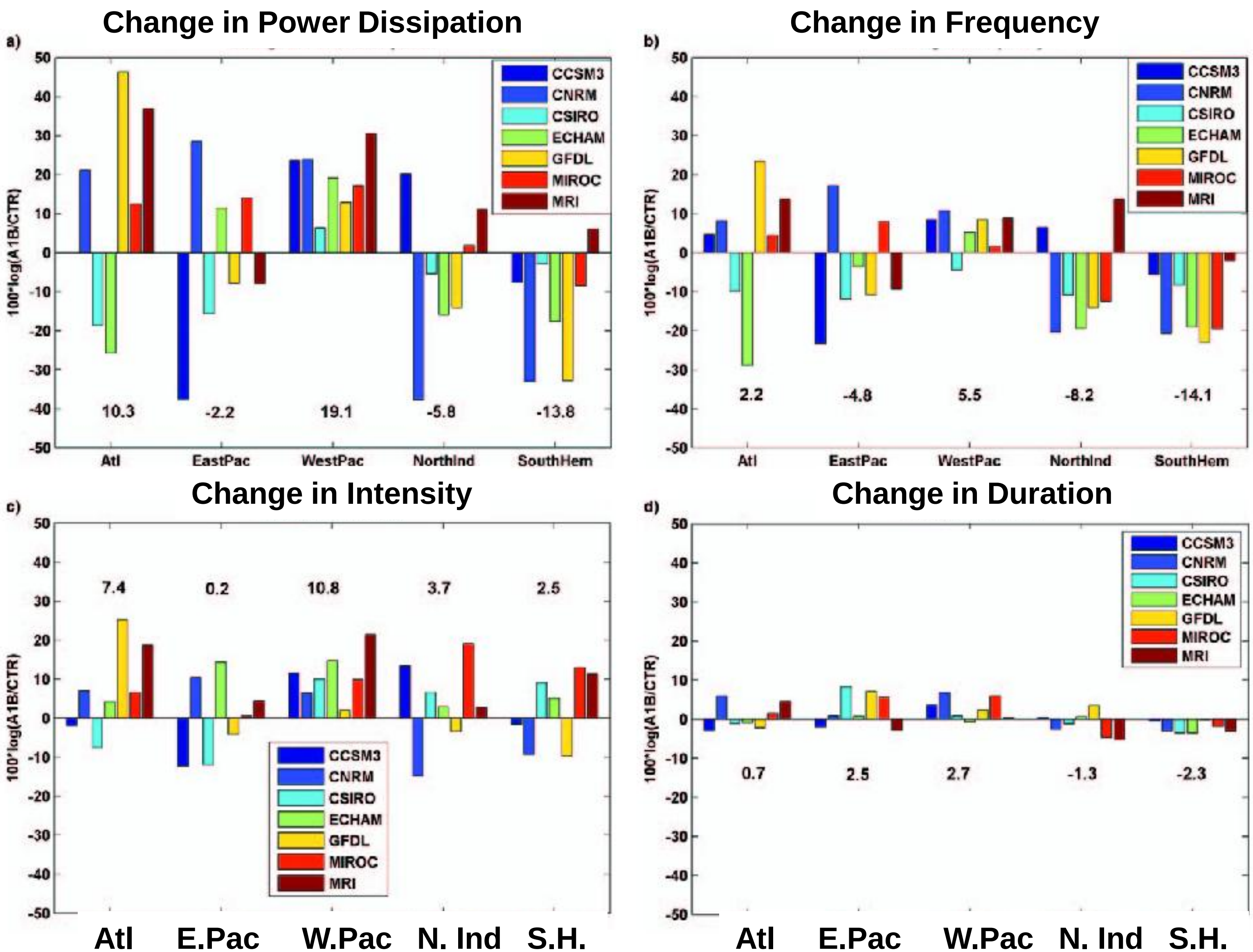
Tropical Cyclones Frequency Projections (Late 21st century) - Summary

Blue = decrease

Red = increase

Source: Knutson et al., Nature Geoscience 2010.

Statistical/Dynamical Downscaling Projections: Emanuel et al. (2008)



Source: Emanual et al. (2008) Bull. Amer. Meteor. Soc.

Table S2. Intensity Projections: Metric/ Reference	Technique/ Model	Resolution/ Metric type	Climate Change scenario	Global	NH	SH	NAtl, NW Pac, NE Pac	N Atl.	NW Pac.	NE Pac.	N Ind.	S. Ind.	SW Pac.
Potential intensity or stat/dynamical projections (% Change)								Avg (low, high)					
Vecchi and Soden 2007 (adapted from ref 60)	Emanuel PI, reversible w/ diss. heating	Max Wind speed (%)	CMIP3 18-model A1B (100yr trend)	2.6	2.7	2.4	2.1	0.05 (-8.0, 4.6)	2.9 (-3.1, 12.6)	3.5 (-6.4 16.1)	4.4 (-3.3, 16.0)	3.7 (-7.6, 17.1)	0.99 (-8.6, 8.6)
Knutson and Tuleya 2004 (adapted from ref 9)	Potential Intensity Emanuel, reversible	Pressure fall (%)	CMIP2+ +1%/yr CO2 80-yr trend				5.0	2.6 (-5.6, 12.6)	7.0 (-1.0, 19.6)	5.4 (-5.0, 21.9)			
Knutson and Tuleya 2004 (ref 9)	Potential Intensity, Emanuel, pseudoadiabatic	Pressure fall (%)	CMIP2+ +1%/yr CO2 80-yr trend				7.6	6.0 (1.6, 13.2)	8.5 (2.8, 25.2)	8.2 (-3.3, 28.0)			
Knutson and Tuleya 2004 (ref 9)	Potential Intensity, Holland	Pressure fall (%)	CMIP2+ +1%/yr CO2 80-yr trend				15.2	12.4 (-4.0, 28.9)	17.3 (9.4, 30.6)	15.8 (3.4, 42.5)			
Emanuel et al., 2008 (ref 21)	Stat./Dyn. Model	Max Wind speed (%)	CMIP3 7-model A1B (2181-2200 minus 1981-2000)	4.5		2.5	6.1	7.4	10.8	0.2	3.7		
Dynamical Model Projections (Max wind speed % change)													
Knutson and Tuleya 2004 (ref 9)	GFDL Hurricane Model	9 km grid inner nest	CMIP2+ +1%/yr CO2 80-yr trend				5.9	5.5 (1.5, 8.1)	5.4 (3.3,6.7)	6.6 (1.1, 10.1)			
Knutson and Tuleya 2004 (Pressure fall) (ref 9)	GFDL Hurricane Model	9 km grid inner nest; Pressure fall (%)	CMIP2+ +1%/yr CO2 80-yr trend				13.8	13.0 (3.2, 21.6)	13.6 (8.0, 16.5)	14.8 (3.6, 25.0)			
Knutson et al. 2001 (ref 61)	GFDL Hurricane Model	18 km grid w./ ocean coupling	GFDL R30 downscale, +1%/yr CO2 yr 71-120 avg	6									
Knutson et al. 2008 (ref 22)	GFDL Zetac regional	18 km	Downscale CMIP3 ens. A1B, 2080-2100					2.9					
Oouchi et al. 2006 (ref 10) (Average intensity)	MRI/JMA Timeslice	TL959 L60 (~20km)	10y A1B 1982-1993 2080-2099	10.7	8.5	14.1		11.2	4.2	0.6	-12.8	17.3	-2.0
Oouchi et al. 2006 (ref 10) (Average annual maximum intensity)	MRI/JMA Timeslice	TL959 L60 (~20km)	10y A1B 1982-1993 2080-2099	13.7	15.5	6.9		20.1	-2.0	-5.0	-16.7	8.2	-22.5
Semmler et al. 2008 (ref 58)	Rossby Centre regional model	28 km	16 yr control and A2, 2085-2100					+4					
Walsh et al. 2004 (ref 59)	CSIRO DARLAM regional model	30 km	3xCO2; 2061-2090 minus 1961-1990										+26% P<970 mb
Bengtsson et al. 2007 (ref 23)	ECHAM5 timeslice	T319 (~40 km)	2071-2100, A1B		+42%, #>50 m/s								
Chauvin et al. 2006 (ref 11)	ARPEGE Climat Timeslice	~50 km	Downscale - CNRM B2 - Hadley A2					 ~0 ~0					
Stowasser et al. 2007 (ref 56)	IPRC Regional	~50 km	Downscale NCAR CCSM2, 6xCO2						PDI : +50%				
Leslie et al. 2007 (ref 57)	OU-CGCM with high-res. window	Up to 50 km	2000 to 2050 control and IS92a (6 members)										+100 % #>30 m/s

Tropical Cyclone Intensity Projections

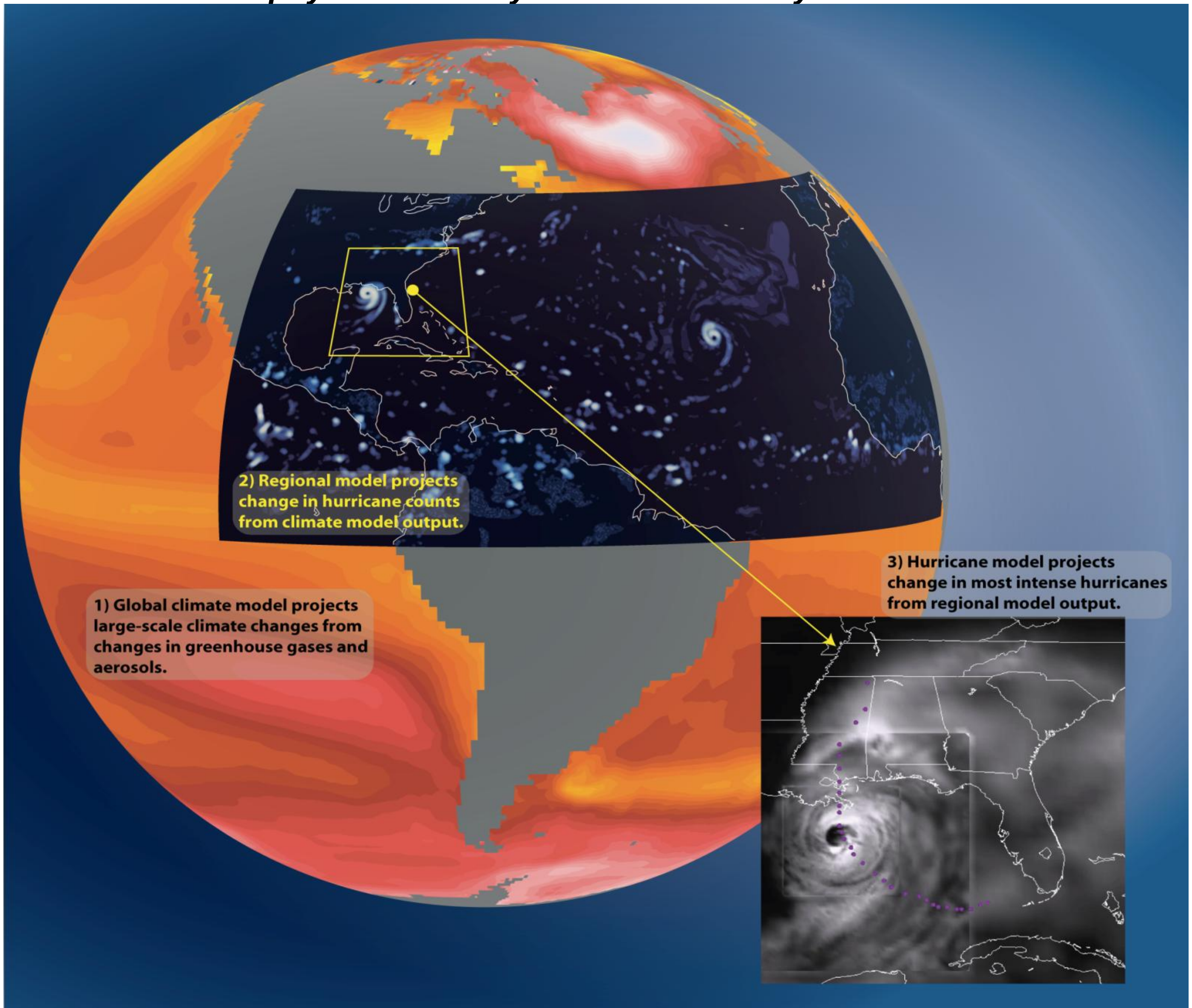
Blue = decrease

Red = increase

Source: Knutson et al., Nature Geoscience 2010.

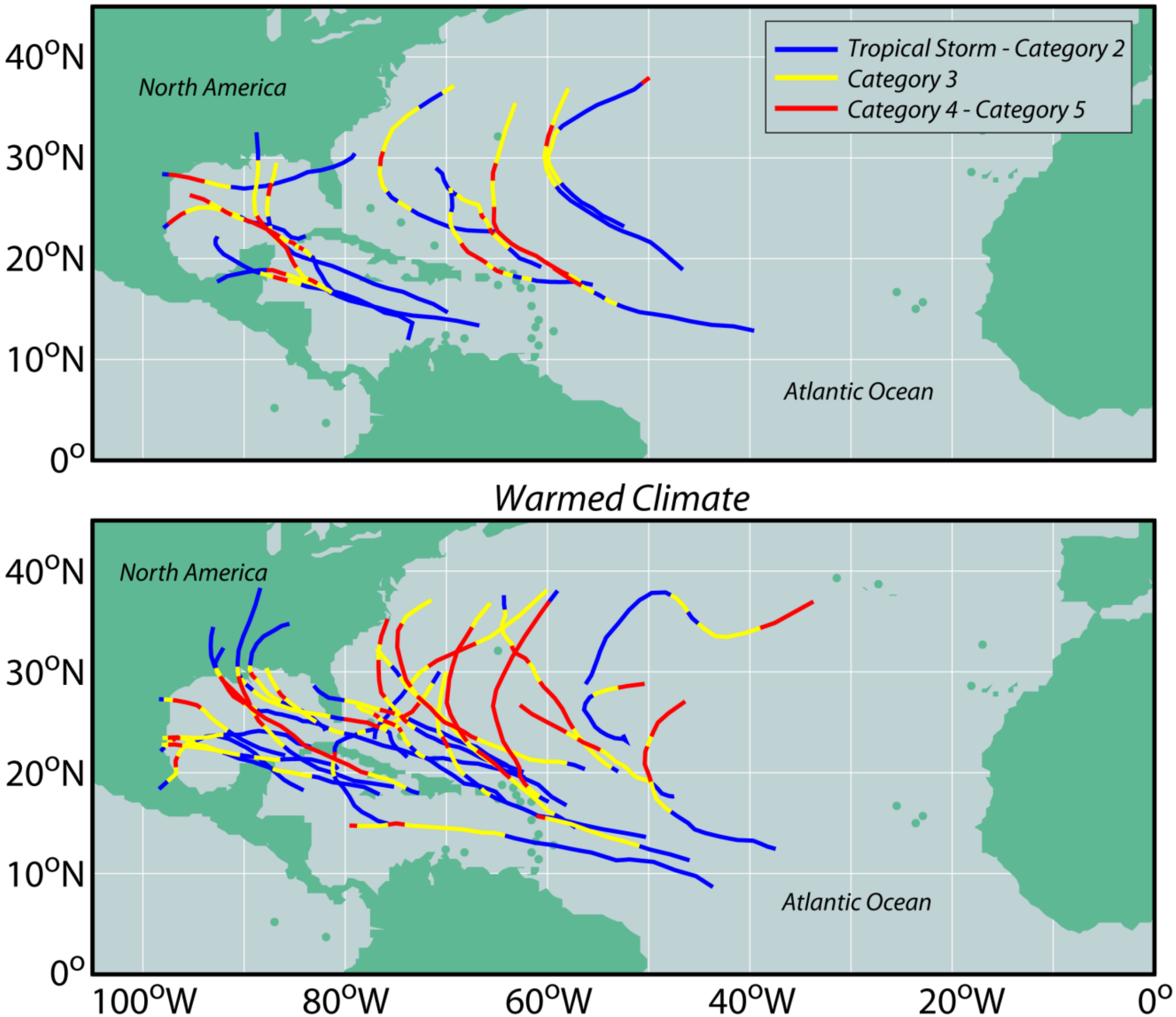
Example of a "double-downscaling" method used to explore frequencies and intensities of Atlantic hurricanes at high resolution

Geophysical Fluid Dynamics Laboratory/NOAA

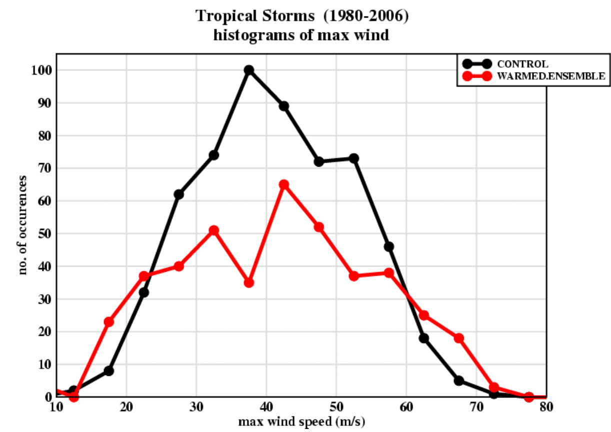


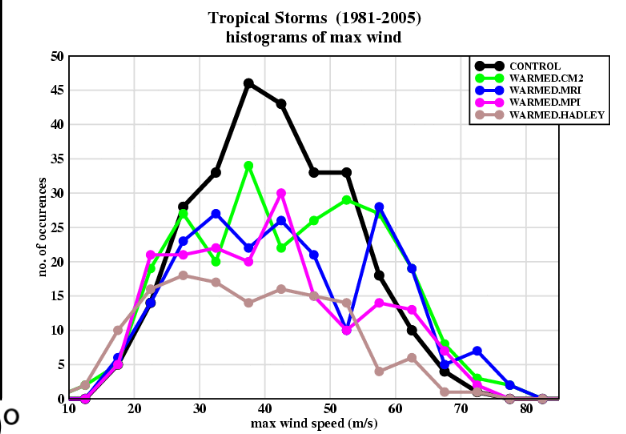
Late 21st Century Climate Warming Projection-- Average of 18 CMIP3 Models

Modeled Category 4 & 5 Hurricane Tracks



The Cat 4-5 increase is not projected for all of the 18 individual models:

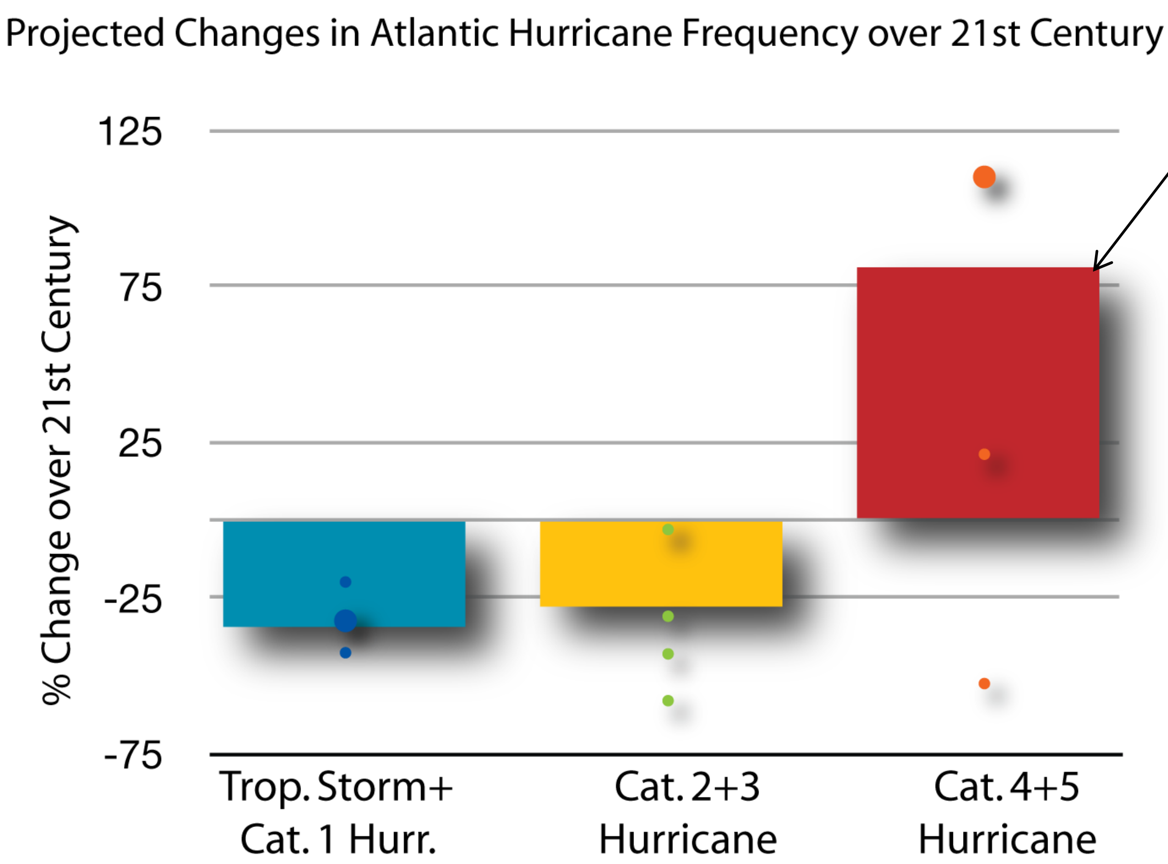




(27 Simulated Hurricane Seasons)

Source: Bender et al., Science, 2010

SUMMARY OF PROJECTED CHANGE



Cat 4+5 frequency: 81% increase, or 10% per decade

Estimated net impact of these changes on damage potential: +28%

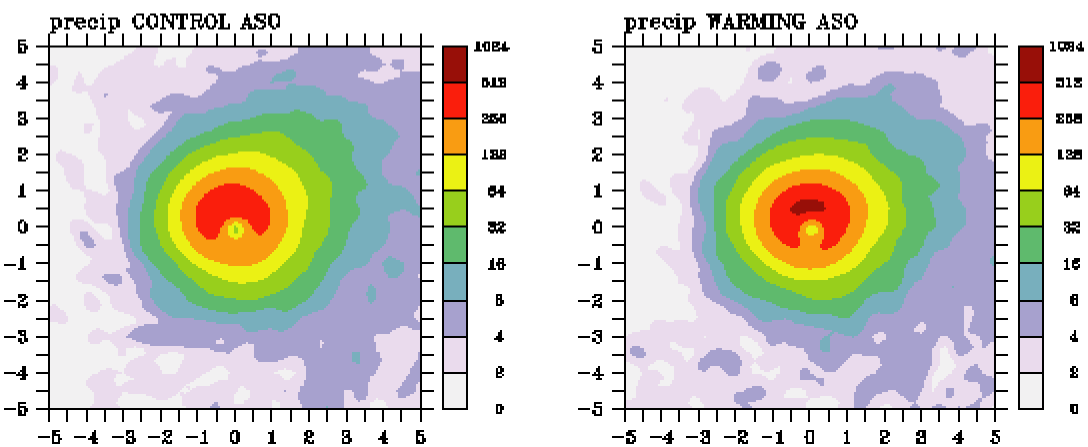
• Colored bars show changes for the18 model CMIP3 ensemble (27 seasons); dots show range of changes across 4 individual CMIP models (13 seasons).

Source: Bender et al., *Science*, 2010.

Tropical Cyclone Precipitation Rate Projections (Late 21st Century)

Blue = decrease; Red = increase

Table S3. TC Precipitation Projections						
Reference	Model/type	Resolution/	Experiment	Basins	Radius around storm center	Percent Change
Hasegawa and Emori 2005 (ref 54)	CCSR/NIES/FRC GC timeslice	T106 L56 (~120km)	5x20y at $1xCO_2$ 7x20y at $2xCO_2$	NW Pacific	1000 km	+8.4
Yoshimura et al. 2006 (ref 55)	JMA GSM8911 Timeslice	T106 L21 (~120km)	10y $1xCO_2$, $2xCO_2$	Global	300 km	+10 (Arakawa-Schubert) ~ +15 (Kuo)
Chauvin et al. 2006 (ref 11)	ARPEGE Climat Timeslice	~50 km	Downscale CNRM B2 Downscale Hadley A2	Atlantic	n/a	Substantial increase
Bengtsson et al. 2007 (ref 23)	ECHAM5 timeslice	T213 (~60 km)	2071-2100, A1B	Northern Hemisphere	550 km Accum. Along path	+21 (all TCs) +30 (TC > 33 m/s)
Knutson et al. 2008 (ref 22)	GFDL Zetac regional	18 km	Downscale CMIP3 ens. A1B, 2080-2100	Atlantic	50 km 100 km 400 km	+37 +23 +10
Knutson and Tuleya 2008 (ref 62)	GFDL Hurricane Model (idealized)	9 km inner nest	CMIP2+ +1%/yr CO_2 80-yr trend	Atlantic, NE Pacific, NW Pacific	~100 km	+22
Gualdi et al. 2008 (ref 34)	SINTEX-G coupled model	T106 (~120 km)	30 yr $1xCO_2$, $2xCO_2$, $4xCO_2$	Global	100 km 400 km	+6.1 +2.8



Knutson et al. (2008)
Avg. Rainfall Rate Increases:

50 km radius: +37%
100 km radius: +23%
150 km radius: +17%
400 km radius: +10%

Average Warming: 1.72°C

<u>SUMMARY ASSESSMENT (other storm characteristics/impacts):</u>

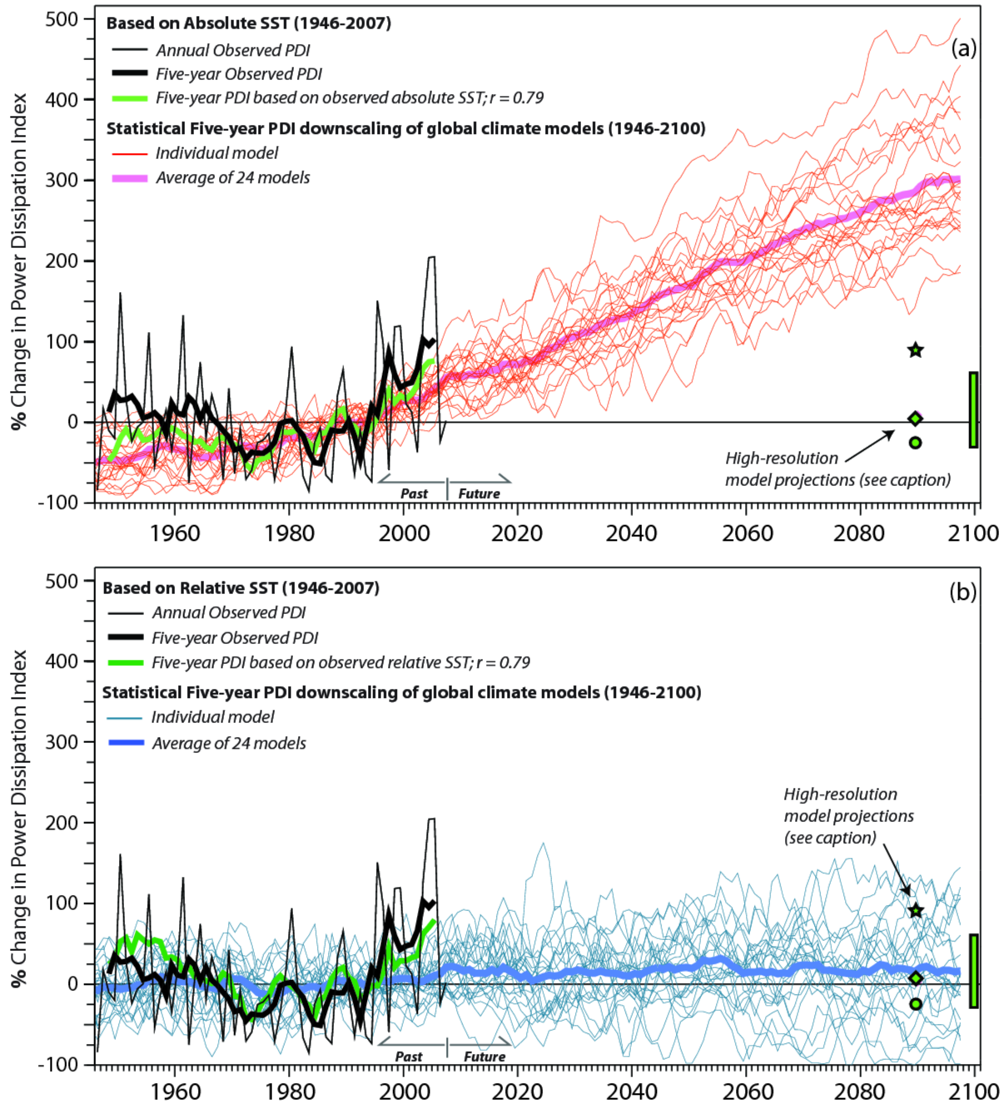
<u>Tropical Cyclone Projections: Genesis, Tracks, and Duration</u>

We have low confidence in projected changes in genesis location, tracks, duration, or areas of impact. Existing model projections do not show dramatic large-scale changes in these features.

‘Possible Range’ of Projections?

Or, speculations on what could make things worse than projected?

Atlantic Hurricane Acitivity vs. Sea Surface Temperature



A significant statistical correlation exists between Atlantic TC power dissipation and SST since 1950 (top).

A comparable correlation exists between the power dissipation and the tropical Atlantic SST relative to mean tropical SST (bottom).

These two statistical relations lead to dramatically different ‘projections’ of late 21st century Atlantic TC activity, ranging from a dramatic ~300% increase to little change. The large (~300%) increase scenario is not supported by existing downscaling models (symbols).

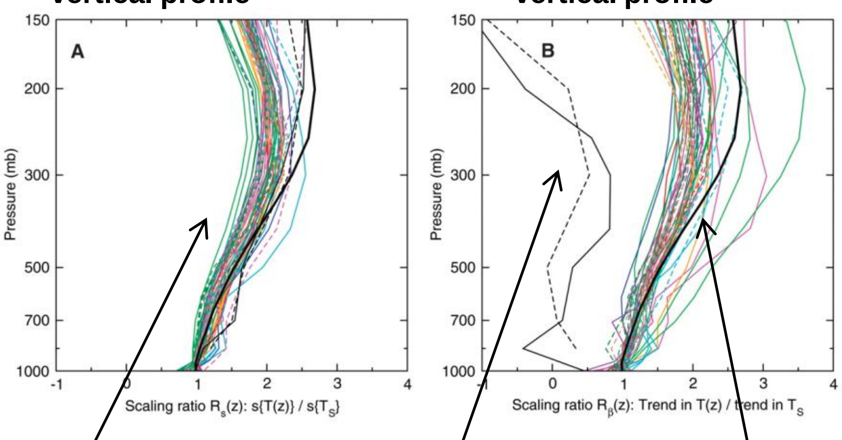
‘Possible Range’ of Projections?

Or, speculations on what could make things worse than projected?

Vertical profile of tropospheric warming:

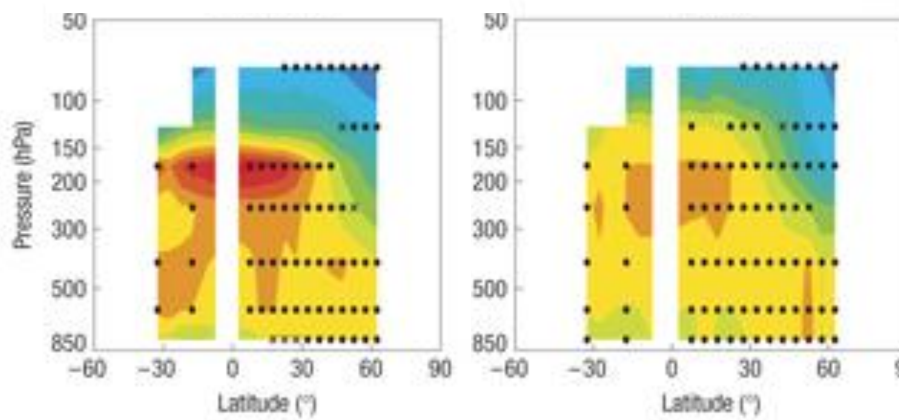
- Models and theory predict that the vertical profile of tropical tropospheric warming will amplify with height, while radiosonde-based and some satellite-based observations suggest that the troposphere has warmed uniformly with height. A uniform warming with height would be ‘de-stabilizing’, and would imply future hurricane activity increases much larger than currently projected (by ~ 3-4x). Modeling studies and critical reanalysis of observations (e.g., using winds to infer temperature trends) suggest that the observed of ‘destabilization’ of tropical temperatures from radiosondes and satellites are likely unreliable.

Interannual Variability vertical profile | **Trend (1979-1999) vertical profile**



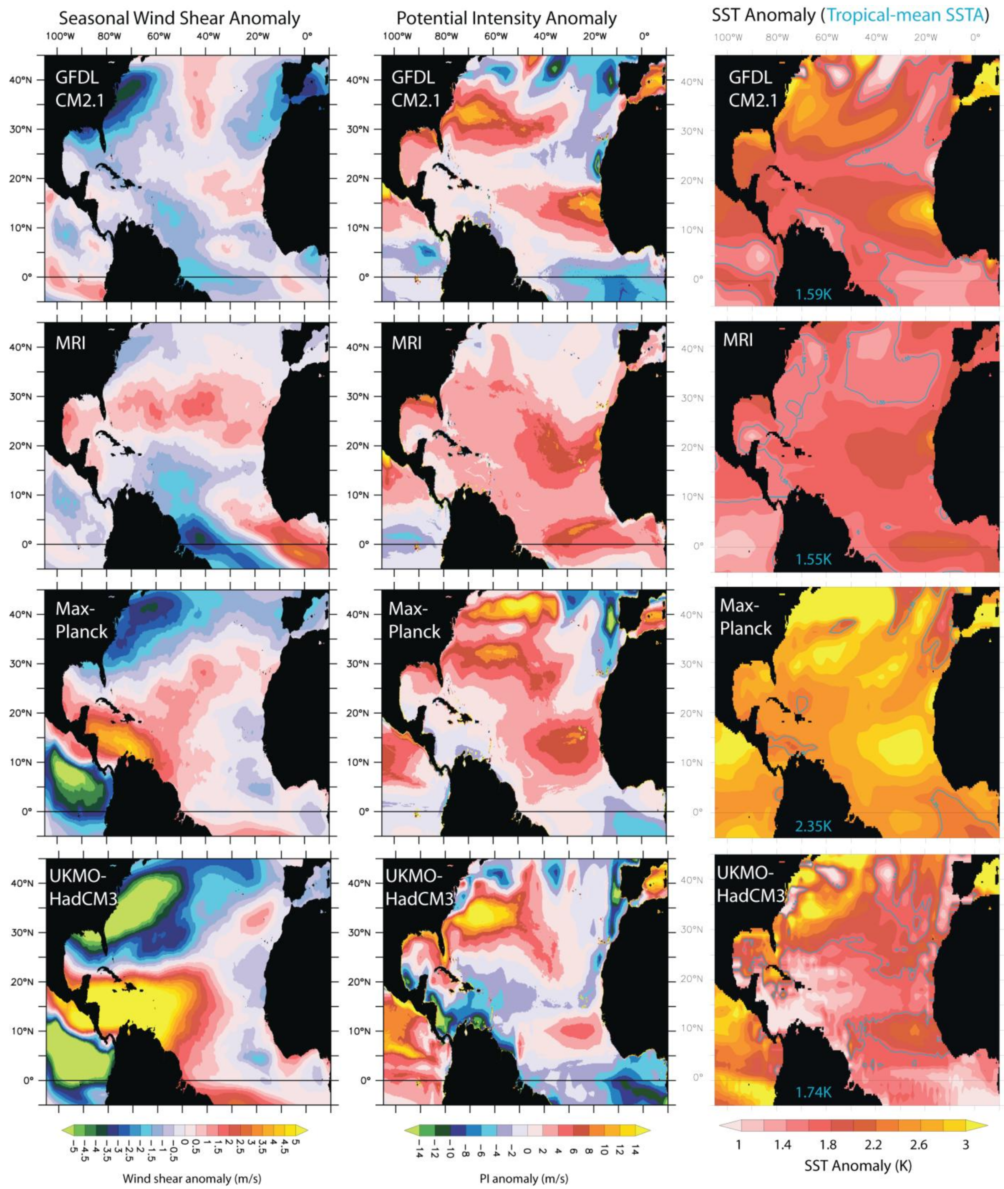
Radiosondes, models and theory | **Radiosondes** | **Models and theory**

Trend (1970-2005) derived from Radiosonde winds | **Trend (1970-2005) from climate models**



Sources: Santer et al. 2005; Allen and Sherwood 2008

‘Possible Range’ of Projections?
Or, speculations on what could make things worse than projected?



The range of possible projections could be even broader than inferred from the AR4 models (sample of 4 models shown at left):

- **IPCC AR4 models favor a weak El Nino-like signature to the pattern of 21st century warming, and strongly favor enhanced vertical wind shear over the Caribbean and tropical Atlantic. However, some models project little change in wind shear and some researchers (Cane et al.) argue that the Pacific warming signal will be distinctly La Nina-like, which could substantially impact Atlantic hurricane projections.**

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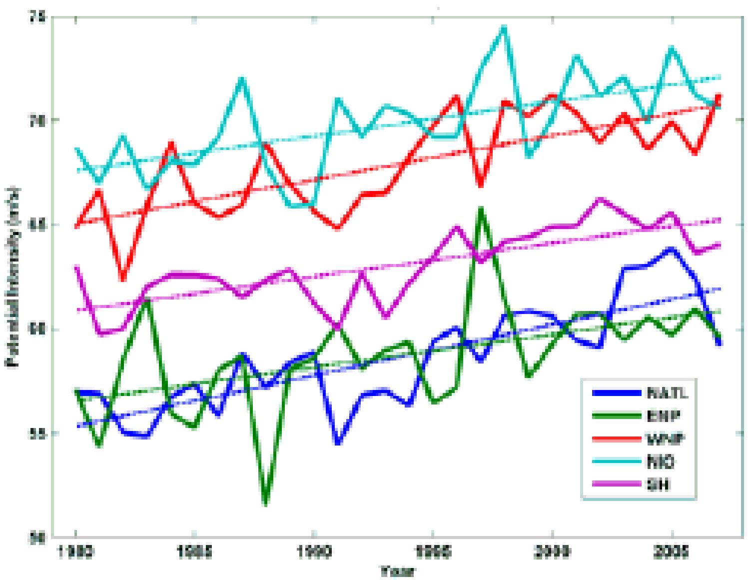
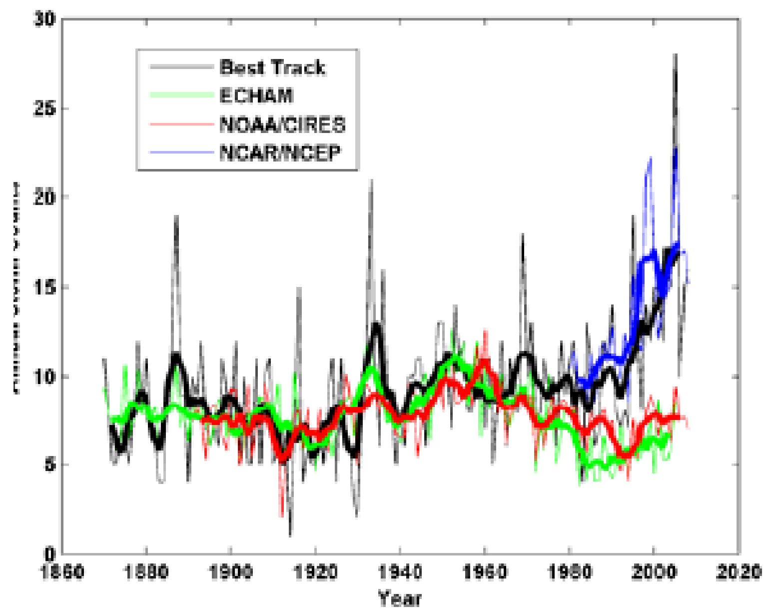
Lower stratospheric temperatures:

- **Can lower stratospheric or tropopause transition layer (TTL) temperatures (apparently cooling) affect tropical storm frequency or hurricane intensity? Emanuel statistical/dynamical downscaling: yes for both. Current GFDL dynamical models: no for tropical storm frequency, not clear for intensity (upper tropospheric temperatures affect hurricane intensity in the GFDL models). Also, are NCEP potential intensity trends since 1980 reliable or do they suffer from inhomogeneity problems?**

Potential Intensity trends since 1980 from NCEP Reanalysis



Statistical/Dynamical Downscaling of Atlantic Tropical Storm Frequency (1870-2005)



Source: K. Emanuel, AMS Hurricanes and Tropical Meteorology Conference abstract, 2010.

‘Possible Range’ of Projections?

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Tropical cyclone-induced changes in ocean heat transport:

- **Possible role of tropical cyclones in ‘equable’ climates of 3-5 million years ago being investigated, but implications for this mechanism on climate for next century or so remain highly speculative. Tropical cyclones cause less than 10% of global poleward heat transport in the current climate, according to the latest studies.**

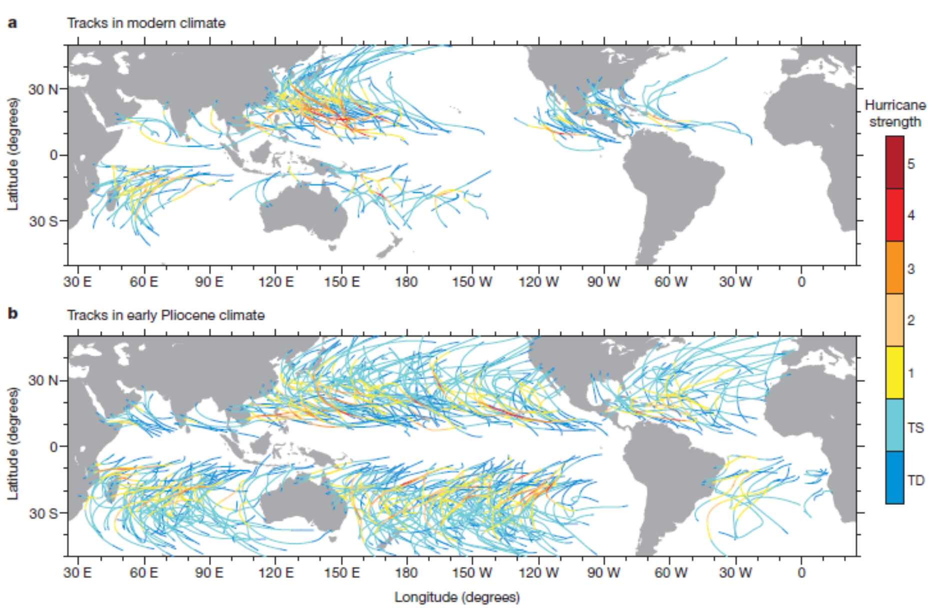


Figure 2 | The tracks of tropical cyclones simulated by the SDSM. a, In the modern climate, and b, in the early Pliocene climate. The colours indicate hurricane strength—from tropical depression (TD; blue) to tropical storm (TS; cyan) to category-5 hurricanes (red). The tracks shown in each p a two-year subsample of 10,000 simulated tropical cyclones.

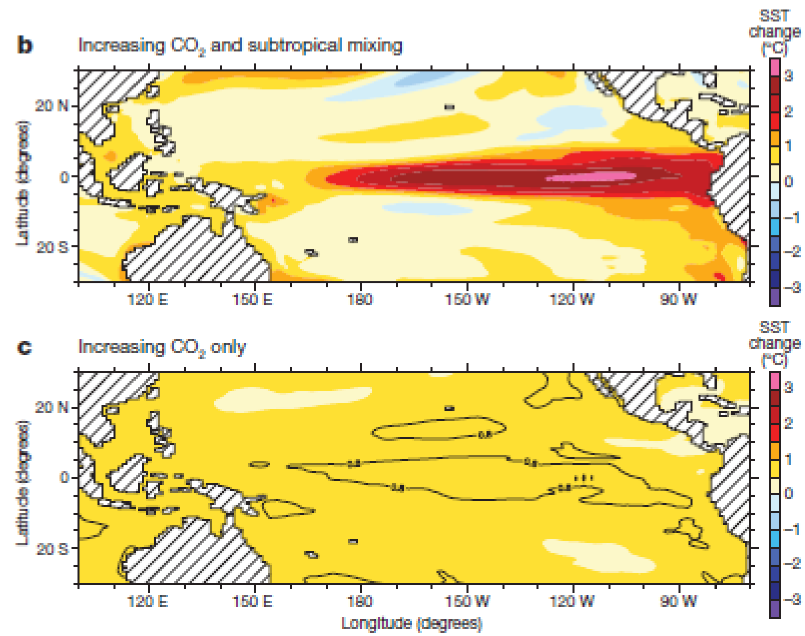


Figure 4 | SST changes in the tropical Pacific simulated by the coupled

Overview of Assessments

Climate Change Detection and Attribution:

- It remains uncertain whether past changes in tropical cyclone activity exceed natural variability levels.

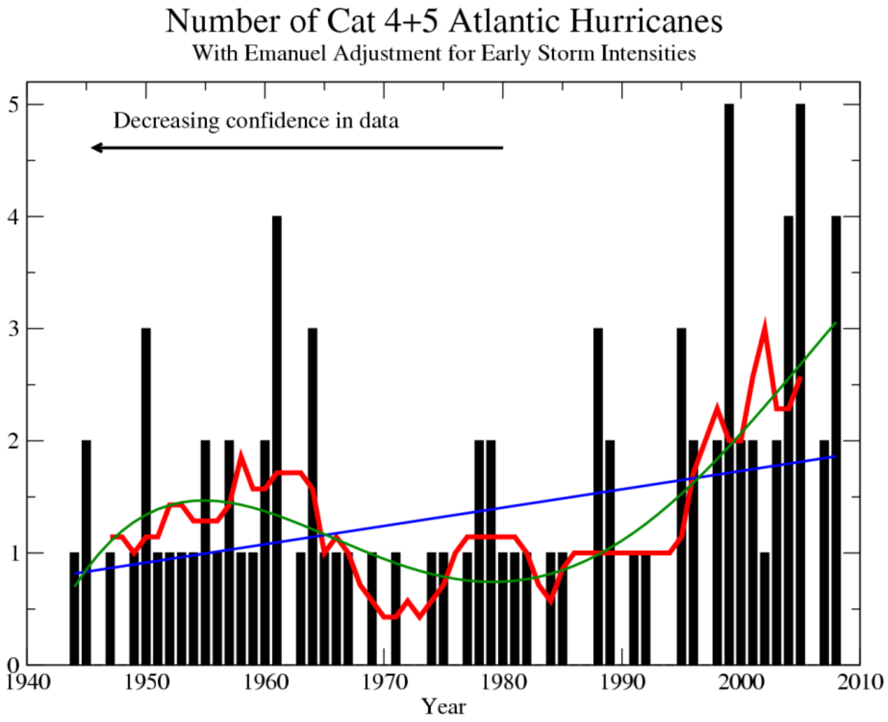
Projections for late 21st century:

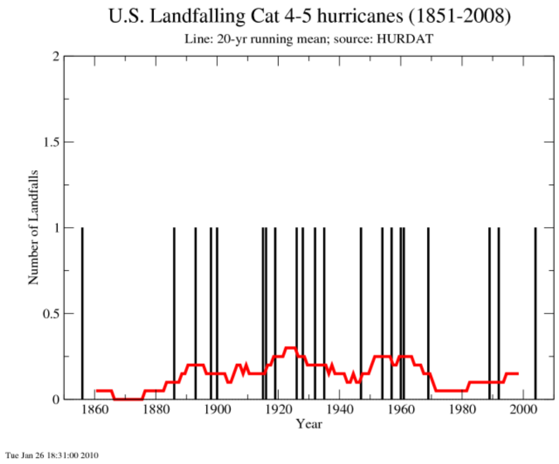
- Likely fewer tropical storms globally (~no change to -34%), with even greater uncertainty in individual basins (e.g., the Atlantic).
- Likely increase in average hurricane wind speeds globally (+2 to11%), though not necessarily in all basins
- More frequent very intense storms (> 50% chance these will increase by a substantial percentage in some basins).
- Likely higher rainfall rates in hurricanes (roughly +20% within 100 km of storm)
- Sea level rise is expected to exacerbate storm surge impacts even assuming storms themselves do not change**.**

<u>Emergence Time Scale</u>: If the observed Cat 4+5 data since 1944 represents the noise (e.g. through bootstrap resampling), how long would it take for a trend of ~10% per decade in Cat 4+5 frequency to emerge from noise?
Answer: **~60 yr** (by then 95% of cases are positive)

Instead, assume residuals from a 4^{th} order polynomial: **55 yr**

Instead, resample chunks of length 3-7 yr: **65-70 yr**





Source: Bender et al., *Science*, 2010.